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PRODUCTION TEST FACILITIES FOR TURBOJET AND TURBOFAN ENGINES - 1975 to 1995

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ABSTRACT:

A review is made of test cell design options in order to identify characteristics of jet engine test facilities to be constructed in the 1970's and designed to be operable for a minimum of twenty years. The necessity of providing replacements for many current facilities is documented, and the factors which will ensure future production capability and economic feasibility are detailed. Present turbine engines are reviewed and projections of future engines and aircraft are made. A confidential supplement is included for qualified receivers.

Experimental investigations of inlet flow patterns and engine exhaust-augmenter relationships are being carried out. Results will be published in thesis form in October 1972, by the Naval Postgraduate School, Monterey, California.

ACKNOWLEDGMENT

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I. INTRODUCTION

Through the 1960's satisfactory engine test facilities consisted of large rainproof buildings located and constructed in such a manner that the nearest neighbors were not permanently deafened. Today, the evolution of aircraft propulsion systems has rendered some of these installations unuseable long before their physical deterioration would have done so. Turbojet test cells constructed during the next decade will be required to meet a greatly expanded and refined definition of satisfactory performance. Factors such as increased thrust, use of high bypass turbofans, proliferation of special-purpose turbine engines, inflation of real estate and utility costs coupled with reduced availability and the recognition of the need for environmental protection will increase the cost and the challenge of designing test facilities operable through the 1990's.

It is the purpose of this report to identify the essential characteristics of the jet engine test facilities to be constructed during the 1970's and to provide a summary of the techniques available to meet these requirements. In the following sections the necessity of providing replacements for current facilities is documented, and the factors which will ensure future production capability and economic feasibility are detailed.

II. ENGINES

A. PRESENT

Aviation Week and Space Technology magazine, in its annual inventory issue, presents a comprehensive summary of the types and sizes of aircraft propulsion systems in use with operational aircraft. The largest in each class is of primary interest to the test cell designer but account must be taken of the wide variation within classes. Within the class of turbojet engines, thrust varies from 30,000 pounds (J58 in the SR 71) to 170 (WR24-7 in drones) and the corresponding lengths vary from 22 to 2 feet.

The facility designed to service turboshaft engines would have to handle variations in shaft horsepower from 5000 SHP (J56-A-15) to 300 SHP (TSE 36) as well as length and weight changes. Similarly, turbofan engines in military use come in one to nine-foot diameters (Harpoon and C5) and have weights of 100 to 7500 pounds. Review of current engine useage makes it obvious that the facility mission must be carefully established prior to initiation of design.

B. FUTURE

In the past, varied aircraft types were powered by similar engines. New technology developments have changed matters dramatically, as evidenced by the present differences between characteristics of high bypass turbofans and afterburning turbojets. Future changes and developments will require more precise matching of engines and airframes for specific missions [Refs. 1, and 2].

The Navy of the future will move strongly towards utilization of gas turbine powered surface vessels. These may be surface effect vehicles (SEV), or standard design vessels, but their propulsion systems will need overhaul and repair facilities similar to those of a Naval Air Rework Facility (NARF).

Because of the vast differences of engine types, it may not prove feasible to build a single test cell capable of testing all engines. Present Navy policy is to assign the overhaul and repair responsibility of a particular type engine to each NARF. The purpose of this section is to correlate engine characteristics and projected aircraft performance.

The first advanced technology engines for Navy fighter aircraft will be used in the F-14 Tomcat. Early versions will utilize the Pratt and Whitney TF-30 412 engine, and F-14B models will be equipped with the more powerful F401 PW 400 engines. The latter engine is in the 20-30,000 pound thrust class and will have an air flow rate at full power of about 300 pounds per second. If an augmentation ratio of 2:1 is chosen a test cell flow rate on the order of 900 pounds per second will result. Other engine manufacturers are also developing afterburner equipped engines in the 25,000 pound thrust category [Ref. 3].

Further fighter aircraft developments will bring to the Navy the ADLI, or Advanced Deck Launched Interceptor. The ADLI will utilize an advanced technology engine with turbine inlet temperatures in excess of 3,000° F. Also, advanced hybrid multicycle engines are being developed and will be introduced to operational use during the life of test cells built in the present decade [Ref. 4]. Turboramjets or supercharged ejector ramjets (SERJ) are also being developed. Discussion of these engines are contained in the confidential supplement to this publication.

Future attack aircraft must combine the capability of high subsonic cruise speeds with the ability to loiter for long periods over target areas. Non-afterburning turbofan engines are presently in use and their continued development and refinement is predicted.

The U.S. Marine Corps presently have the Harrier (AV-8A) in operational use. The Navy may move toward procurement of Harrier aircraft in the near future and advanced vectored thrust V/STOL aircraft within the next ten or fifteen years. The Harrier utilizes the Pegasus turbofan engine with variable nozzles which is built by Rolls Royce. The advanced Pegasus 15 will have 25,000 pounds thrust and an airflow requirement of 450 pounds per second. A requirement for testing these engines is that shrouds and ducts be installed for directing the exhaust streams of the individual nozzles into a common exhauster [Ref. 5]. Total cell requirements for this engine will also be 900 pounds per second with a 1:1 augmentation ratio.

The Navy is currently developing the S-3 carrier based ASW aircraft, which is powered by the General Electric TF-34 turbofan engine. This is a 9,000 pound thrust engine with an airflow capacity of about 300 pounds per second, and will be the first engine that the Navy operates that will be tested in the same configuration as it is mounted on the aircraft. That is, it will be pylon mounted, thereby requiring an overhead thrust bed. Because of the large mass flow through the turbofan engine any pressure variations in the cell acting across the fan exhaust will cause errors in thrust measurement. The TF-34 has a bypass ratio greater than 6:1. Because of the exhaust characteristics of turbofan engines care must be taken in matching the engine and augmenter to avoid excess air entrainment over that which is required for cooling purposes, thereby increasing the cell depression [Ref. 6].

Future patrol aircraft developed to be introduced in the 1980's may utilize large fan engines. Other aircraft using the same type engines may be those developed to replace the Navy's present transport fleet. Military transports with STOL capability will require turbofans in the 25-30,000 pound thrust category [Ref. 7]. The airflow through an engine of this size will be on the order of 1,000 pounds per second and total cell airflow could run as high as 2,000 pounds per second, depending on the augmenter design.

Smaller logistic aircraft, successors to the C-2 COD aircraft, may use turbofans in the 5-10,000 pound thrust class. These will be similar to the above-mentioned TF-34 in flow requirements, and test facility requirements will be similar as well.

Future weapons system acquisition will have a bearing on aircraft design, and therefore on engine design. Work is presently being done to develop laser weapons for aircraft use. For some missions, the effectiveness of this weapon is proportional to the power which can be generated in the transporting aircraft and such systems may require a platform as large as the Lockheed C-5A [Ref. 8]. If the Navy were to acquire such a system for strategic defense, it would find itself in possession of turbofan engines in the 50,000 pound thrust category, having airflow requirements of 1,500 pounds per second and requiring a test facility capable of handling 3,000 pounds per second airflows.

Consideration also must be given to the testing of turboshaft engines used in large rotary-wing aircraft. Facilities must be available for the measurement and absorption of the shaft energy generated by such engines. Similarly, turbine engines used for surface ship propulsion systems will require complex gearing and energy absorbing systems [Refs. 9 and 10].

Other trends in engine/airframe mating techniques will require some modification of test cell design and operation. The F-14 aircraft will utilize non-interchangeable left hand and right hand engines. This may mean that reversible mountings, slave accessories and so forth will be required in cells.

In order to minimize drag associated with nozzle and airframe interaction, non-axisymmetric nozzles may be employed in the future.

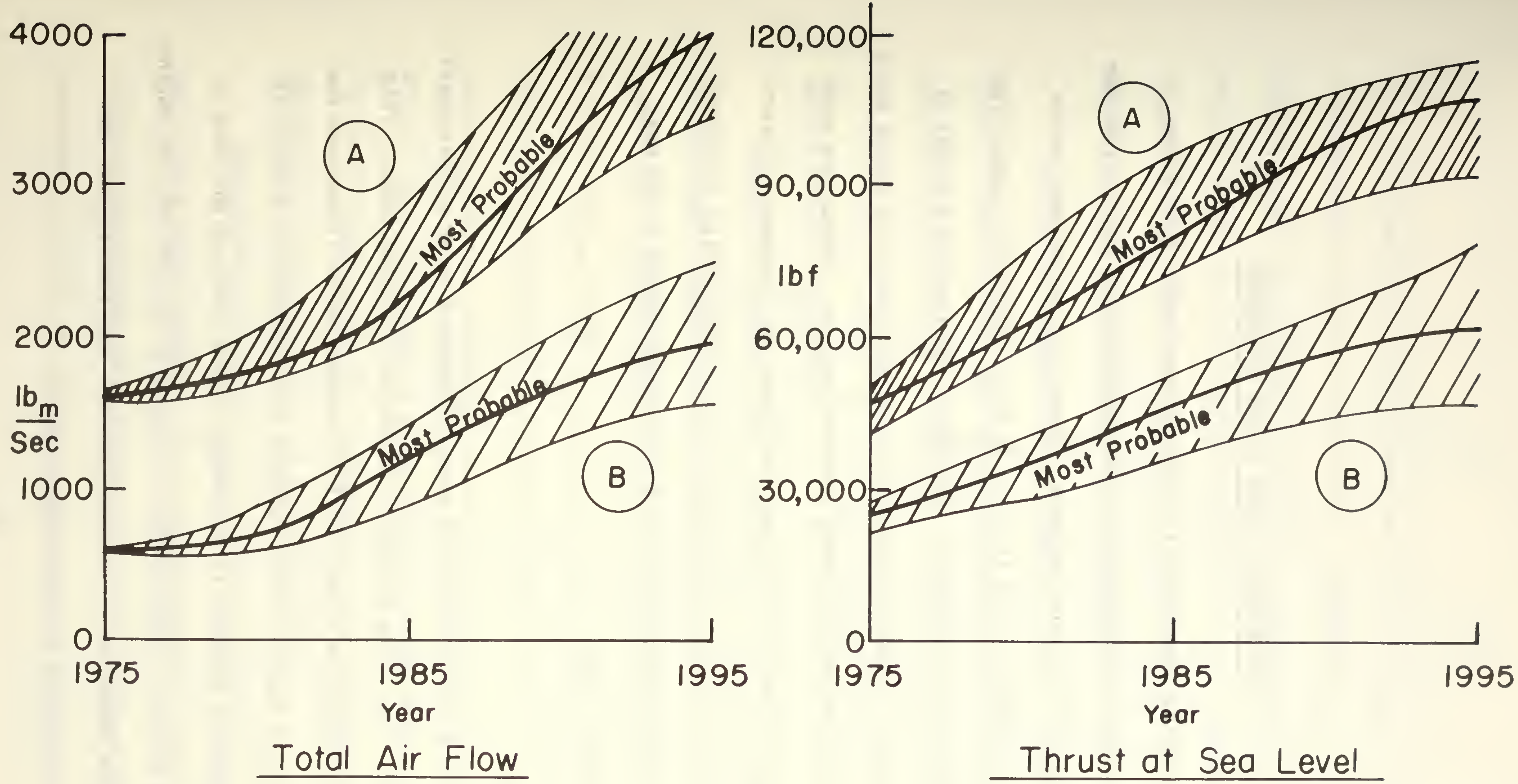
This possibility implies a requirement for an augmenter tube designed to permit replacement of the receptor bellmouth.

Knowledge of systems on the horizon which may eventually become operational is essential to provide flexibility and long life for projected test facilities. Prior to test cell design initiation, the update of each subject must be accomplished.

III. SUMMARY OF TEST FACILITY REQUIREMENTS

Figure 1 is the most accurate summary of test cell requirements available from current sources. As with any forecast, it includes some uncertainty; but the information included is as authoritative as possible, having been collected from engine manufacturers, Department of Defense planning agencies, published reports of service sponsored research, and interviews with facilities planners for several test cell operators. These data makes it clear that the decision as to facility capacity will restrict usage plans for extended periods and that the operator will require guidance by policy level managers to determine final construction requirements.

Gerend [Ref. 11] provides a simple method of predicting turbine engine weights and dimensions. This method has been used to check the credibility of this summary information. These projections are specifically confined to facilities for sea-level testing only. Forecasts of requirements for altitude test facilities are available in Refs. 12 and 13.



(A) — Full Service Facilities

(B) — Facilities Limited to Fighter/Attack A/C

Test Facility Requirements 1975 — 1995

Figure 1.

IV. PRESENT TEST CELL DESIGNS

Many currently operational jet engine test cells, both in the military and civilian communities, were designed and built to test the early generations of turbojet engines. These may be defined as the state of the art engines of the 1950's. In other instances, some even older test cells are in existence. The Naval Air Rework Facility at NAS North Island, California has several operational cells which were initially built to test reciprocating aircraft engines. These are still in use testing J-57 and J-79 engines, but their performance is marginal now and will be aerodynamically and environmentally unsatisfactory for the engines which will reach operational status in the next twenty years [Ref. 14].

A. INLETS

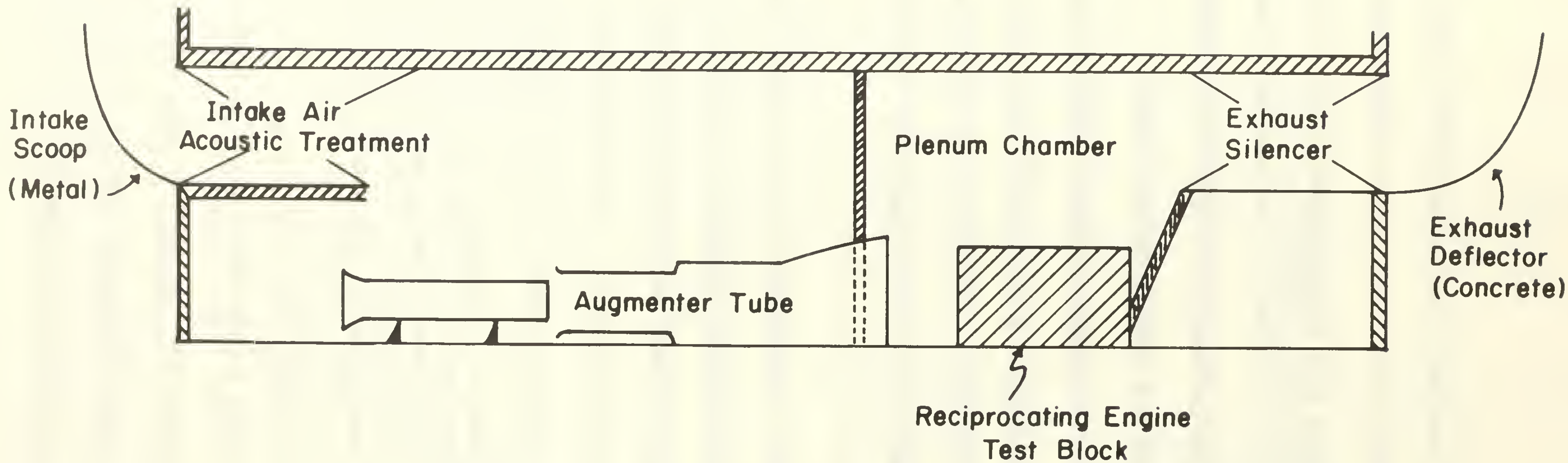
Many of the oldest test cells were engineered so as to take maximum advantage of existing construction and to minimize costs. This practice is illustrated in Figure 2 which schematically illustrates the characteristics of the two oldest turbojet test facilities at NAS North Island. Of primary interest is the design of the inlet and the lack of consideration given to requirements for uniform airflow into the engine. The large block shown in the plenum chamber was the original test stand for the testing of reciprocating engines.

The next generation of test cells was designed with some added sophistication. It was realized that the test section itself should be long enough to provide for some flow straightening forward of the engine bellmouth. Such cells are typified by the installation shown in Figure 3 which depicts the general design of NARF North Island's depot level test cells designed and built in the late 1950's.

The cell aerodynamics are obviously cleaner than those previously shown, and in operational use with present afterburner equipped engines they have been satisfactory. In all such installations certain compromises are made between the desired operational characteristics and economic constraints.

Modern turbine engines, particularly turbofan engines, have proven highly sensitive to aerodynamic distortion in poorly designed test cells. Large engines such as the General Electric CF6 and the Pratt & Whitney JT9D are built without inlet guide vanes, and, as a result, any distortion in the inlet flow field can have an effect on engine operation. General Electric considers total pressure distortion greater than two inches of water above or below the mean measured at the fan or compressor face unacceptable, and endeavors to reduce this difference to less than one inch H_2O [Ref. 15].

Modern test facilities built to test these large fan engines, as well as any future engines, have been designed to reduce inlet distortion as much as possible. United Air Lines' overhaul facility in San Francisco exhibits one of the simplest inlet designs. Air enters through



Test Cells 13, 14 Nas North Island.

Figure 2.

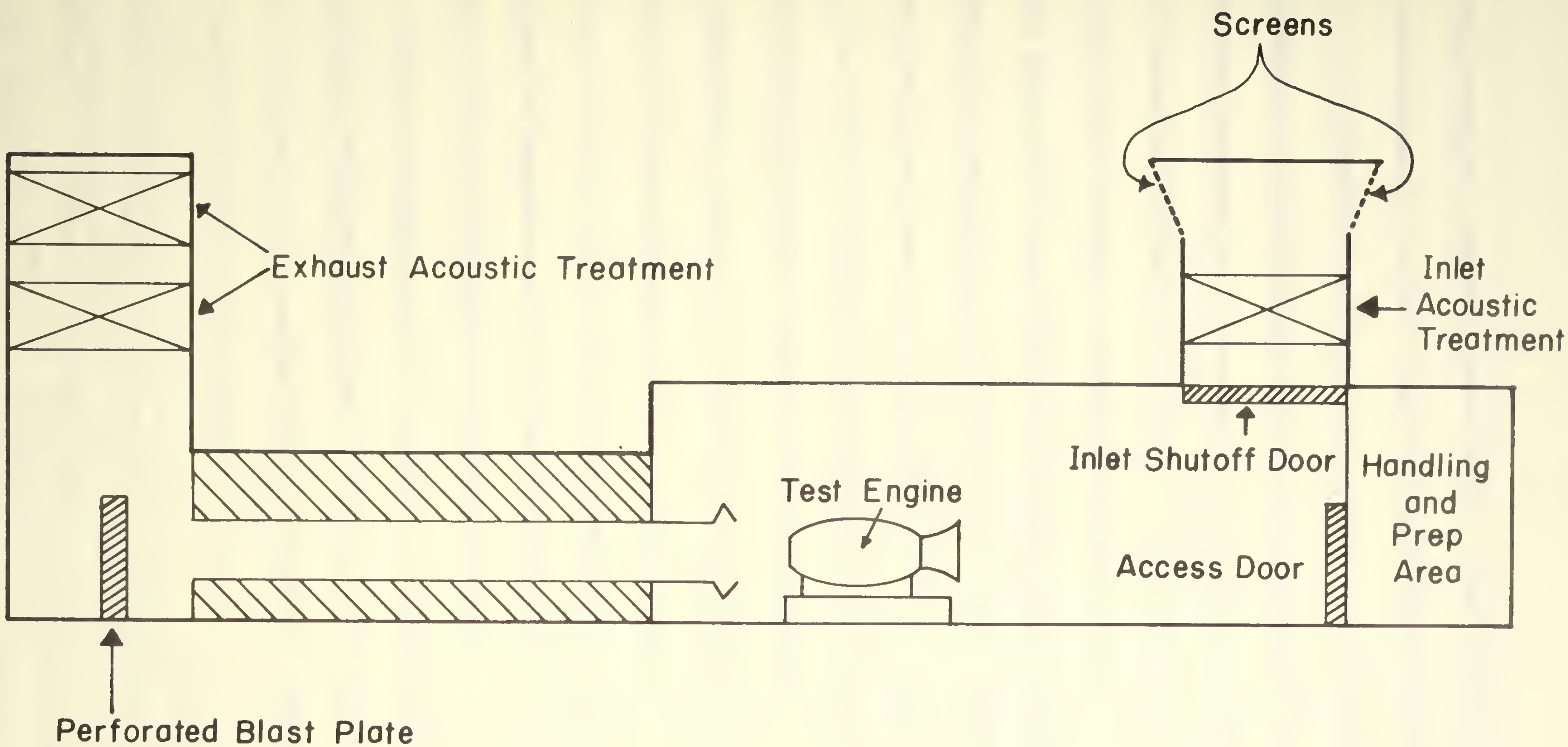


Figure 3. Test Cells 19 and 20, Nas North Island.

the horizontal inlet, passes the acoustic treatment and enters the test section without encountering any turns. This design is obviously easier to construct than one having a large vertical inlet.

A second example of modern design philosophy is exhibited in the test cell operated by Pacific Airmotive Corporation in Burbank, California. The vertical inlet is flush with the roof structure; turning vanes are installed to minimize the losses caused by the 90^{o} turn. Turning vanes or flow straighteners will become increasingly necessary as test cell airflow design limits are approached. Some modern cells are designed so that turning vanes may be added in the future. The installation operated by AiResearch Manufacturing Co., in Torrance, California, has a vertical inlet. The only present requirement for flow treatment is a corner fairing to reduce separation at the inlet bend, but designs have been drawn up for the addition of turning vanes when future requirements so dictate [Ref. 16].

A prime consideration in the use of flow treatment is the method of installing the engine in the test cell. The simplest and cheapest method of construction is to build a front-loading cell. However, if flow treatments are installed, this design requires that they be movable or that a portion of the treatment be hinged.

B. EXHAUSTS

The basic philosophy of present exhaust treatments is to remove the majority of the kinetic energy from the jet exhaust, to cool the exhaust by mixing with secondary air or water, and to lower the noise level of the exhaust. Removing the kinetic energy is also a method of acoustic treatment. The most common method of accomplishing the first two objectives is to utilize the kinetic energy of the exhaust to pump secondary air through the cell and into the exhauster or augmenter tube where mixing of the two streams occurs. Augmentation ratio, defined as the ratio of secondary air mass flow to engine air mass flow, is an important consideration in determining overall cell design. With an excessive augmentation ratio the depression limits of the cell may be exceeded; with too small a ratio, desired cooling may not be accomplished, and temperature limits of test cell exhaust components such as installed acoustic treatment may be exceeded. Present design goals for augmentation ratios are 2:1 for turbojet engines and 0.25:1 to 0.5:1 for high bypass turbofan engines [Refs. 5, 12, and 15]. Some facilities, however, still have augmentation ratios as large or greater than 1:1 for large turbofan engines [Ref. 17]. Turbulent mixing phenomena are not well understood, and much work remains to be done in analyzing the ejector system.

Water cooling is usually required for an engine operating in afterburner; the augmentation ratio required to cool the exhaust without water is greater than 6:1. The minimum amount of water usage is desirable in order that water supplies be preserved. Many cells utilize spray rings mounted inside the augmenter. These operate very inefficiently because of the difficulty of pentrating the hot, high speed core of the exhaust [Ref. 18]. Several attempts have been made to

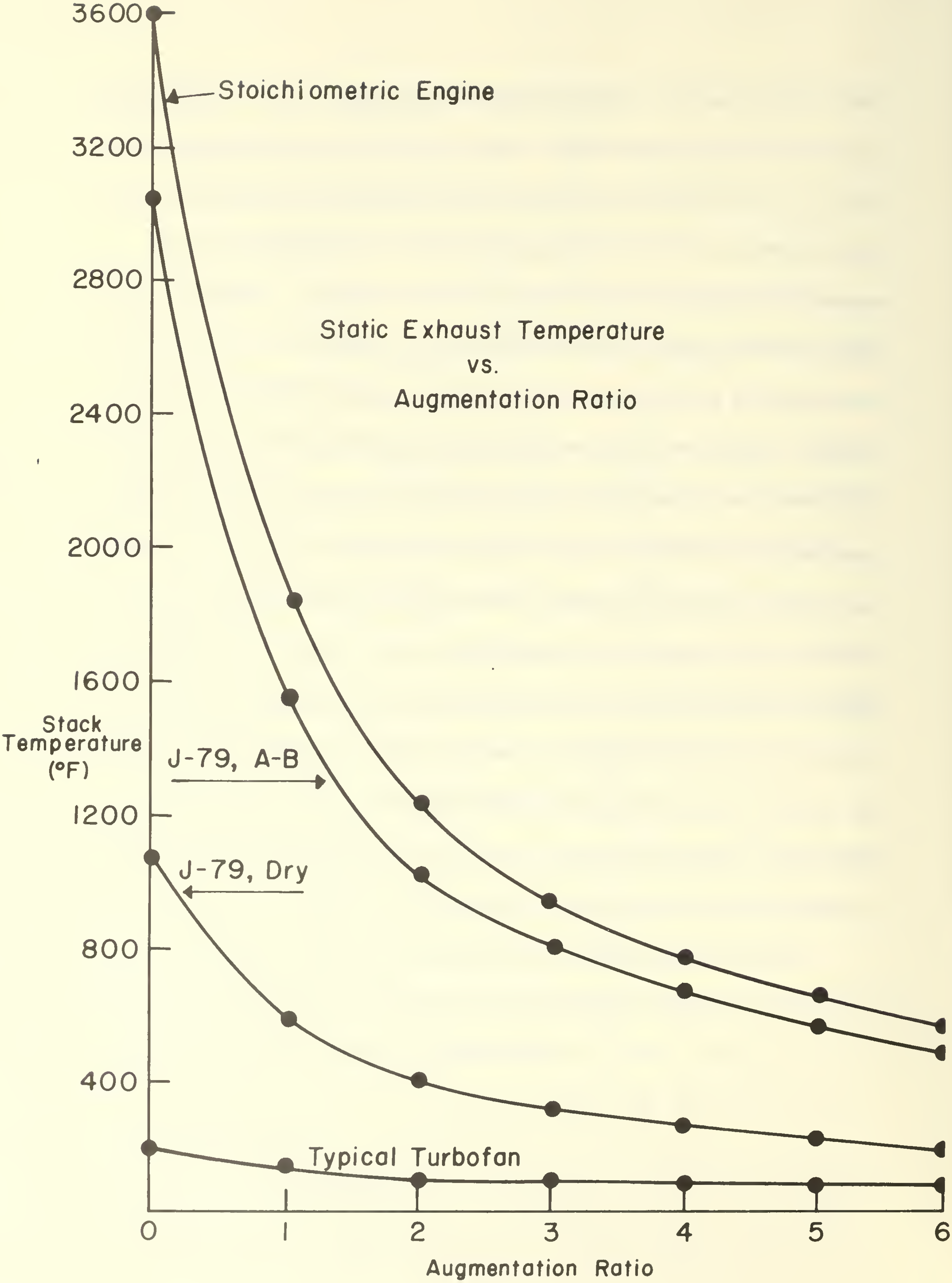

3600
3200
2800
2400
2000
1600
1200
800
400
Stoichiometric Engine
Static Exhaust Temperature
vs.
Augmentation Ratio
Stack
Temperature
(°F)
J-79, A-B
J-79, Dry
Typical Turbofan
0
1
2
3
4
5
6
Augmentation Ratio

Figure 4.

inject the water from within the core itself. The water sparger [Ref. 19] is an example. Care must be taken in the design of such items, since they can produce undesirable acoustic phenomena if their natural frequencies correspond to the driving frequencies of the exhaust. Further development of water injection is a necessity for economical future operation.

One method available for removing the kinetic energy of the jet exhaust is the "brute force" method. At NARF North Island in cells 13 and 14 [Fig. 2], the exhaust impinges on a solid concrete block, lined with steel plate. This is effective in destroying the continuity of the stream, but has failed to prevent serious damage to the walls of the plenum chamber [Ref. 14]. In the newer cells at North Island the exhaust impinges on a perforated steel plate [Fig. 3].

A newer method of treating the flow, one coming into more general use [Refs. 16, 17, 20, and 21], involves a colander in the form of a cylinder or a cone. The colander is the last section of the ejector tube, and is perforated with holes, usually on the order of 1-1/4" in diameter [Ref. 15]. This serves to break up the flow and changes the low frequency noise of the exhaust into more easily attenuated higher frequencies. Work remaining in this area involves the study of placement and sizing of the holes so that uniform flow in the exhaust stack is attained.

Other methods of exhaust treatment will become necessary in the future. Environmental protection standards will require pollution abatement systems for engine test facilities. These systems will require close matching between the engine nozzle and the exhauster, because any excess mass flow will unnecessarily load the abatement equipment. Also, in some cases, the flow needs to be properly conditioned before it reaches the abatement system [Ref. 22].

C. GENERAL

Because of the relatively small flow rates, older turbojet engines could be tested in close proximity to cell boundaries. The larger engines now coming into use must be tested with adequate clearance from floors, walls and ceilings to reduce velocity distortions. This clearance can only adequately be provided by overhead thrust bed systems. Because thrust measuring devices above the engine are subject to conductive heat transfer they must either be monitored for temperature changes or kept at a constant temperature. United Air Lines' facility in San Francisco has both such systems installed [Ref. 17]. Current thrust measurement accuracy is typically $\pm$ 56 lbs. for an engine thrust of 41, 100 lb. [Ref. 23].

Overhead mounting systems have introduced a new problem to test operations in that the height of the engine when mounted in the cell makes accessibility difficult. United Air Lines has installed a hydraulically lifted platform beneath the mounting system. During actual testing the platform is lowered to a position flush with the floor, providing smooth passage for the secondary air past the engine [Ref. 17]. Another solution to this problem was developed for the previously mentioned AiResearch facility [Ref. 16]. The work platforms are suspended from the overhead at a convenient height, and are swung up and locked next to the ceiling during engine operation.

In many older cells considerable time is used in preparing and mounting the engine for test. If this time is kept to a minimum, total cell running time can be maximized. Modern design philosophy reduces the man-in-cell time by allowing much of the preparatory work to be done in the handling area rather than in the cell itself. In the handling area the engine is fitted to a specially designed adapter. Necessary engine connections for starting air, fuel, instrumentation leads, and external power are made to the adapter. The entire assembly is then moved to the cell area, and is hoisted to the thrust bed by a winch assembly in the thrust bed itself [Refs. 16, 17, and 20].

Means of handling and transporting the engine are also varied. Many facilities use wheeled dollies for transporting the engine and related assemblies [Refs. 16 and 17]. Some newer facilities utilize overhead monorail systems both in the handling and preparation areas and in the cell itself [Refs. 19 and 24]. Some problems have developed with monorail systems, however, and complete flow analysis must be accomplished before utilizing such a handling system. In one situation [Ref. 19], it has been found that vortices are formed by flow interaction with the monorail, causing serious flow distortion in a cell designed to test large turbofan engines.

Recently, attempts have been made to improve operator visual contact with the interior of the cell. The usual method of providing this contact is to provide a window between the control room and the cell. Whenever the cell structure is penetrated, additional acoustic problems are created; in order to provide minimum noise levels within the control room there should be no direct connection between the cell and the control room. One alternative to windows has been to install closed circuit television. NARF North Island has installed three black and white cameras in their large cells. These cameras have no zoom or pan capability, and have not met with complete operator approval. Also, they do not obviate the need for entrance into the cell by technicians to check for fuel or oil leaks when the engine is operating.

Because of the varied engines which must be tested in one cell, consideration must be given to the ease with which cell hardware can be adjusted for various engine sizes. NARF North Island utilizes the movable augmenter concept. The United Air Lines facility uses a jackscrew arrangement to adjust the thrust bed position. The range of adjustment will depend on the size of engines projected to be tested and the means of providing adjustment is up to the option of the designer.

Modern test facilities are being equipped with automatic data acquisition and processing capability. AiResearch Manufacturing Co. has an excellent example of a system designed for developmental engine testing and United Air Lines possesses a system designed for production testing of overhauled and repaired engines [Refs. 16 and 17].

Most of the above information is applicable to depot level test cells for large overhaul facilities. Other proposals have been made for developing smaller test cells for use in intermediate level maintenance facilities. The Ground Support Equipment division of the Naval Air Engineering Center, Philadelphia, Pa., has designed the cell shown in Figure 5. This design differs greatly from those discussed in this section. A primary difference is the construction technique utilized. The cell shown is constructed from pre-fabricated sections and is designed to be demountable if the need should arise. The flow design is different in that separate intakes are provided for the primary (engine) and secondary (augmentation) airflows. Complete aerodynamic analysis is required for this and other major design alternatives.

A listing of some persons and firms conversant with current test cell design philosophy is given in Appendix B.

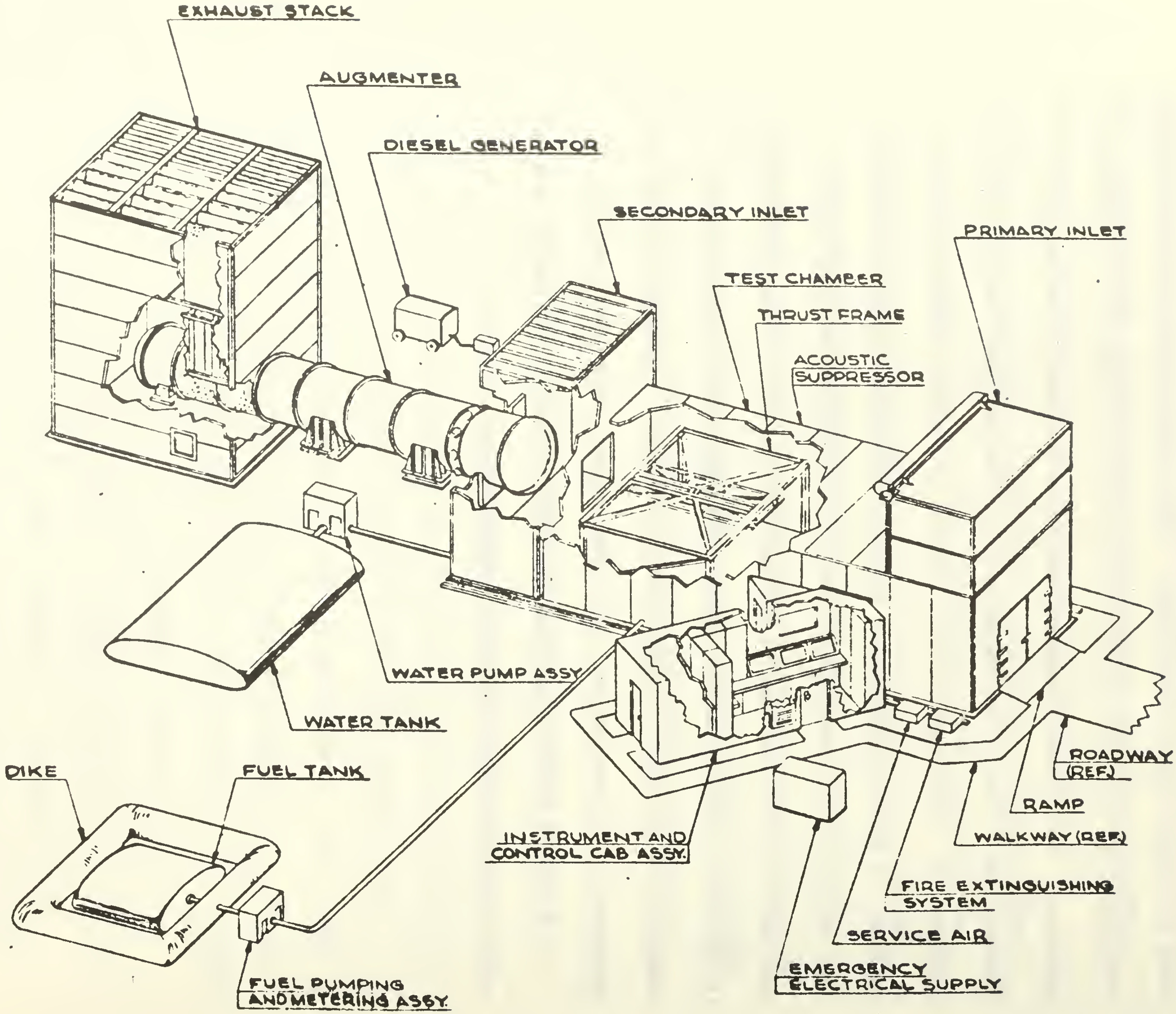


Figure 5. Demountable Test Cell.

V. DESIGN OPTIONS

A. INLET

1. Acoustic Control

The current development of commercial STOL aircraft and increasingly stringent airport noise level restrictions [Ref. 25], have resulted in extensive on-going research directed at reduction of engine generated acoustic power. It is reasonable to expect that the engines now in service will be the noisiest, per pound thrust, with which new test cells must cope [See Fig. 6], [Refs. 26, 27, and 28]. It is equally certain that new test cells will require some form of inlet acoustic treatment for the following reasons:

a. Current, noisy engines will still be in service after the anticipated introduction of the replacement cells [Ref. 28].

b. Turbofan engines increase the acoustic power directed upstream into the inlet [Refs. 27, 29, and 30].

c. Military aircraft will continue as the least restricted in required acoustic abatement by virtue of their mission and environment [Refs. 31, 32, and 33].

d. The test cell structure alone will not be able to absorb the acoustic power produced by even the quietest of

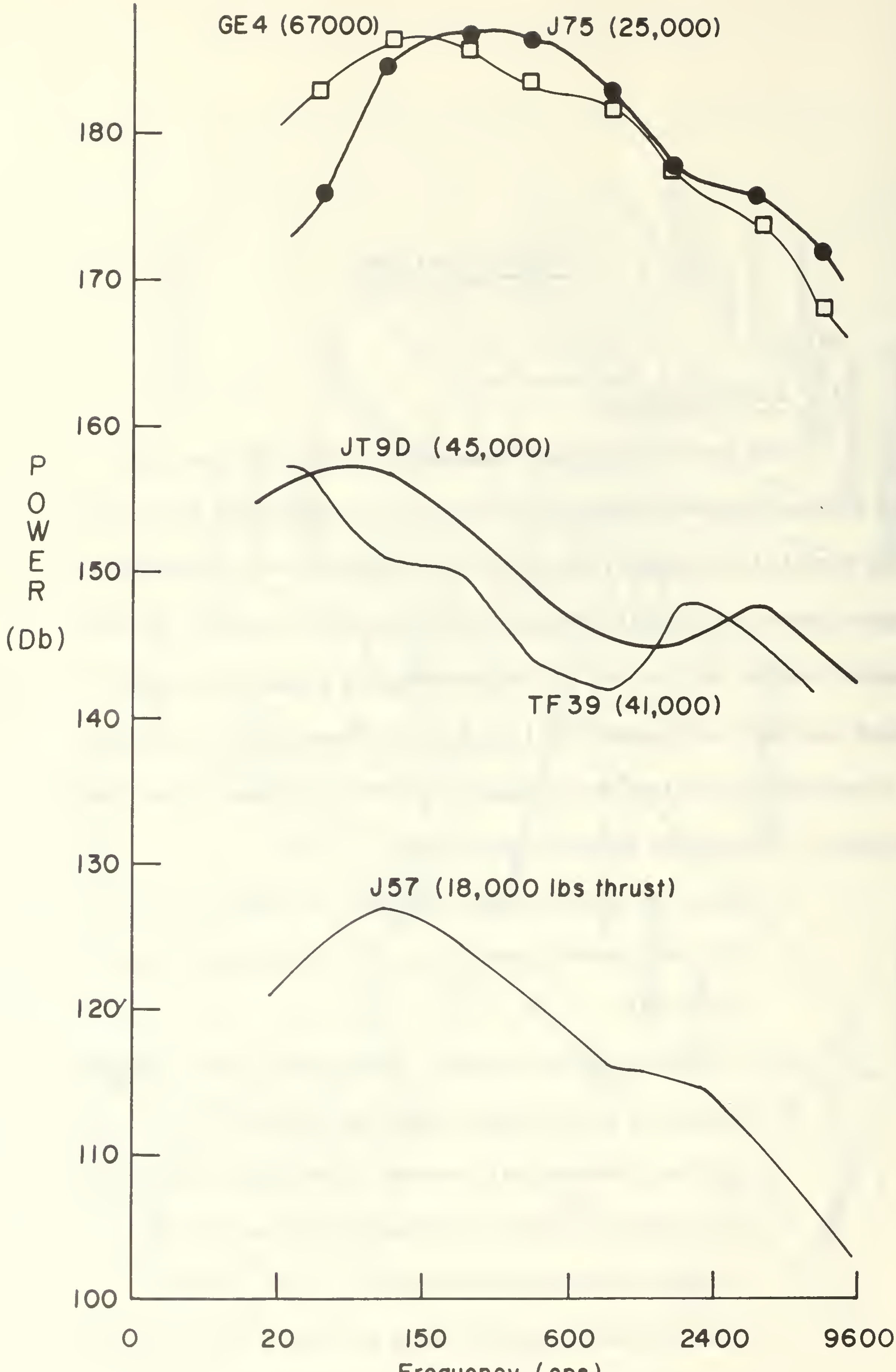


Figure 6. The effect of engine type and thrust on sound power levels.

projected future engines [Refs. 12, 25, 26, 27, 28, 31, 32, and 33].

Accepting the necessity of including specific acoustic treatment several options are available [Fig. 7]. Many of the designs for which performance data are available are proprietary ones and the cost of acquisition must be weighted against that of locally produced designs which must be oversized to compensate for the less complete information on effectiveness.

Flat baffles are the simplest of the duct obstruction types. Of sheet metal and fiberglass composition they can, with careful streamlining, provide acceptably low levels of flow distortion. Adjustment of length, thickness and spacing can match acoustic absorption characteristics to specified frequency ranges. The overall flow length required to meet both acoustic and aerodynamic limits may be the greatest for this option and the increased cell length or stack height must be off-set by simplicity of installation and replacement. Both proprietary and non-proprietary designs are available [Refs. 12 and 28].

Staggered baffles require less total flow length for the same absorption and produce less aerodynamic distortion than the flat types. They are also more difficult to construct and replace though reduced total size may ease handling difficulties [Refs. 28 and 34].

The sinuous passage treatment requires a length and produces a distortion level intermediate to those of the two baffle types. Construction and installation is more difficult and expensive than

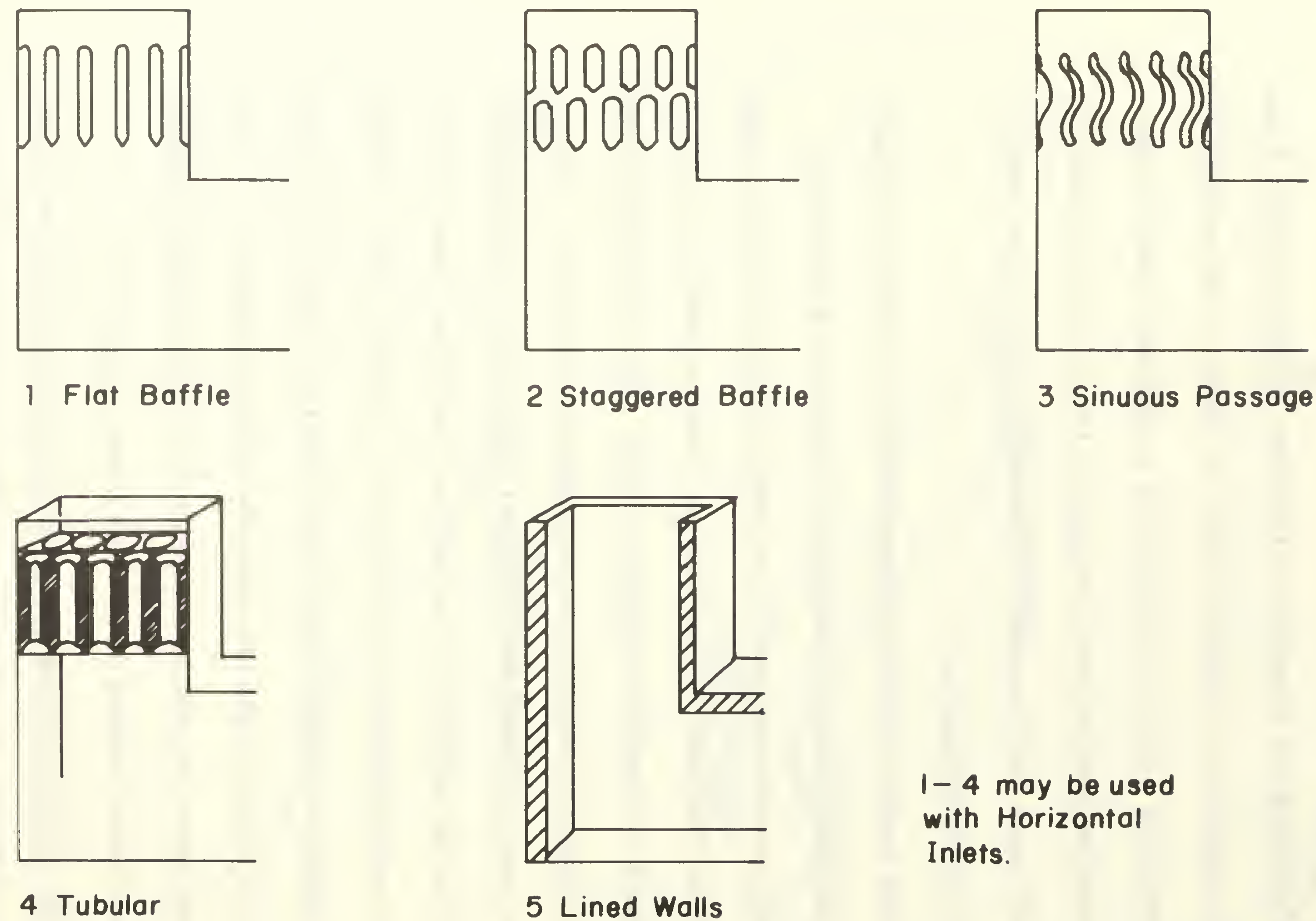


Figure 7. Inlet Acoustic Treatment Options.

either of the baffles, but proprietary designs are available which permits single panel replacement [Refs. 28 and 33].

The acoustic performance of the tubular treatment reduces the total flow length required below that of the other options but the distortion level in some operating conditions may demand an increase in mixing length which offsets this gain. Additionally they may prove incompatible with good turning vane performance when used in a vertical inlet. The available designs with adequately documented performance levels are proprietary in nature [Refs. 25 and 29].

Another option which is not in current use and which remains to be fully evaluated as to effectiveness is the lined wall concept. By lining the considerable wall/overhead area foreward of the engine inlet with suitable foam and lead septum material it may be possible to entirely eliminate the need for duct obstructing devices with consequent simplification of distortion control. Since considerable absorbing thickness could be provided at low cost in a test cell, this option must be considered. Preliminary analysis by the treatment manufacturer indicates that this method would be restricted to a vertical inlet arrangement. The lining material is available from commercial sources and it would be necessary to obtain their assistance in determining the type and quantity required [Ref. 29].

Any of these alternatives can provide the required acoustic control and except as noted do not restrict the selection of inlet position. Detailed investigation is required to evaluate the possible trade-offs in cost, size, service life, and distortion. The construction contractor will require the services of a qualified acoustic engineer, but satisfactory inlet acoustic treatment can be provided at reasonable cost. Doelling and Bolt [Ref. 35], provide an excellent summary of calculation procedures for design use. Before final selection can be made the designer must, of necessity, consider compatibility with the aerodynamic requirements detailed in the next section.

2. Aerodynamics

Comprehensive design criteria are not available for this aspect of the inlet design. No general method is available for the prediction of streamline, pressure, or velocity patterns though these may limit the total test cell in its compatibility with future engines. Reference 12 is an example of a completed construction specification which ignores this requirement entirely and depends on luck for satisfactory operation. The designer has available the choice of:

a. Inlet shape: horizontal, vertical, inclined, open ended or capped;

b. Number of turns, radii and flow lengths;

c. Shape of the flow dividers used in acoustic control;

d. Duct shape: expanding, contracting, constant area; open or vane guided turns,

e. Duct wall finish: protrusion streamlining, the shrouding of fittings and the installation of boundary layer trips or vortex generators [Ref. 36].

The following diverse factors must be considered in selecting from these options.

a. Cost and availability of real estate at the proposed site.

b. Effect of inlet stack height and position on the reingestion of exhaust gas.

c. Required cell air flow capacity.

d. Allowable pressure and velocity distortion of the flow at the engine inlet [Ref. 37].

e. Allowable cell depression.

f. Requirements for emergency airflow shut off to permit CO_2 flooding.

g. Local weather conditions, especially winds.

h. Construction cost per square foot of cross sectional area and foot of length.

Of these factors, a, g, and h, may be accurately determined following the selection of the construction site. Analysis of the effect of stack height and position requires that the exhaust treatment type and pollution control system be identified. In general, with exhaust directed vertically, increasing the inlet height and reducing inlet-to-exhaust separation distance reduces the probability of avoiding recirculation problems. A horizontal inflow naturally reduces the likelihood of exhaust gas capture [Refs. 38 and 39]. The references provide reasonably accurate prediction methods for proposed design susceptibility to recirculation.

Determination of the total inlet flow capacity requires identification of maximum projected engine requirements and facility type. With this available [Fig. 1], it is necessary to select the augmentation ratio for the cell. Again, this can not be freely chosen but is fixed by choice of exhaust treatment system since the various types have widely different requirements for excess air. Since a continuing trend toward higher exhaust temperature is evident in Section II excess air to cool this exhaust will go the same way. Since this capacity may limit the facility growth potential and excess capacity is low in maintenance cost, it should be maximized consistent with construction costs. References 37, 28, 32, 12, and 40 illustrate typical current and anticipated augmentation requirements. From these a total airflow capacity three times the maximum engine requirement can be justified.

Since test cell operation ideally simulates free atmosphere engine performance the approach velocity is limited in modern facilities to a maximum of 50 feet per second [Refs. 28, and 37]. This is an arbitrary limit, but is reasonable since increasing velocity above this point rapidly increases the cost of distortion control, increases cell depression and decreases the accuracy of thrust measurement data. Accepting this limit, cross-sectional area required is available and depression per foot of flow length may be accurately estimated using the standard duct flow loss techniques of Refs. 41, 42, and 43. Various depression limits have been used in design of current facilities but general agreement is found in considering the depression to be a free variable and altering the design to change it only in the most extreme cases; i.e., those in which pressure loads approach the structural load limit [Refs. 37 and 40]. The effect of greatly increased mass flows on depression and required cross sectional areas is demonstrated in Fig. 8.

In the past, with these estimates, the designer could produce construction blueprints for the inlet. Prior to the introduction of the turbofan engine the production test cell was required to produce a specified quantity of air at a reasonable velocity at the engine inlet. Only the grossest mismatch of engine/cell sizes or the ingestion of objects other than air molecules could produce compressor stall, flow reversal, overtemp or unstable engine oscillation. Today, test cells can be and are built which have more than sufficient inlet flow capacity but which can not be used to test the engines for which they were designed [Refs. 37 and 10]. The condition responsible is non-uniformity of pressure or velocity distribution at the engine inlet. Turbofan engines, both high and low bypass, and special-use, lift type engines are the most sensitive to this distortion [Ref. 44], but when it exists it affects every engine tested to an unpredictable extent. Its sources are numerous and effectively include everything in the cell between the open atmosphere and the engine face which is in other than a straight smooth-walled duct [Refs. 37, 45, 46, 47, and 48].

The design of distortion free inlets is an empirical matter with even the most experienced contractors in the field [Ref. 34]. Until

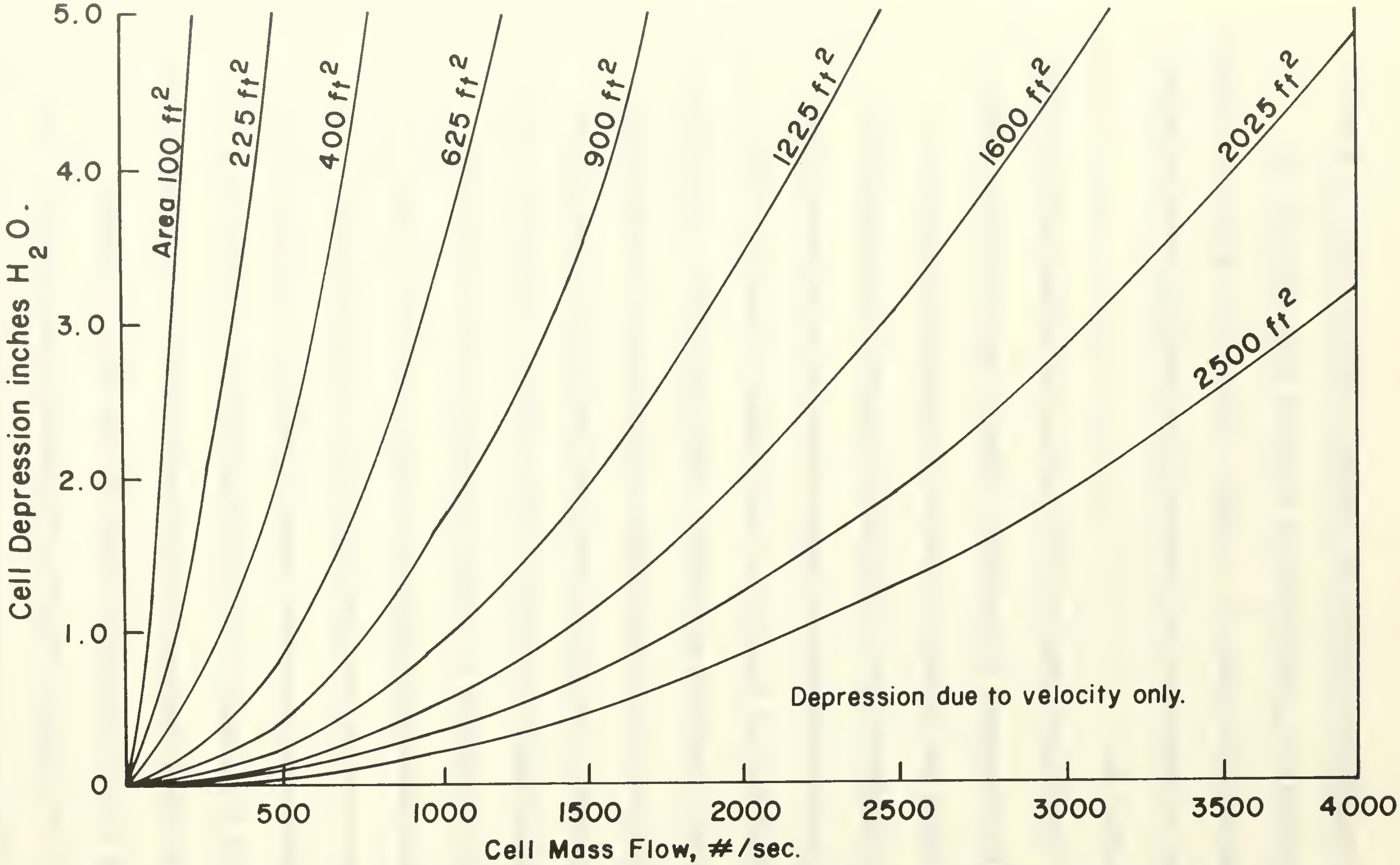


Figure 8. Effect of Increased Mass Flow on Cell Depression and Required Area.

a method becomes available to predict the flow distortion for a projected engine in a proposed cell with variable augmentation ratio, the designer must accept the necessity of the following restrictions:

a. Minimize the number of turns in the inlet.

b. Place no flow dividing surfaces in the inlet which are not absolutely necessary.

c. Streamline all surfaces confining the flow or immersed in it.

d. Provide flow length forward of the engine for vortex and wake damping [Ref. 33].

e. Construct and test models of proposed designs [Ref. 49].

f. Provide turning vanes [Ref. 34], and flow straighteners for cell operations near design flow capacity.

g. Test the finished cell with reasonable completeness at all flow levels and augmentation ratios.

h. Employ aerodynamic methods in the design of duct curves [Refs. 50 and 51].

Reference 33 indicates an empirically determined pressure distortion maximum of $\pm$ 0.25 in H_2O. The persistance of wakes generated by flow obstructions may be estimated with the methods of Refs. 52, 53, and 54. However, total distortion can not be accurately predicted and no fixed limits have yet been established by test cell operators or designers. Distortion indices have been published by many manufacturers for production engines. Definitions vary but each index may be measured by pressure survey rakes located forward of the compressor face. The variation with engine speed of this index may be measured for a given engine type in a particular cell and the limit which will cause engine surge or stall is then available. Unfortunately, there is no method for predicting the value of the distortion index for a proposed cell design. Extensive investigation has also failed to establish useful correlations between test cell stall margin and that of the same engine installed in an aircraft [Ref. 55]. Therefore, the best the designer can now do is to conform to the above guidelines and include provisions for repeated aerodynamic monitoring of cell performance throughout the service life of the facility. Current research may vastly simplify this aspect of design and increase confidence in the final performance of future high capacity cells [Ref. 56]. For current installations distortion caused by inlet vortices may be reduced after discovery by the employment of wall or deck fences or aspirated plates [Ref. 36].

3. Maintenance and Safety

Aside from basic structural integrity of all components, the contribution of inlet design to safe cell operation has been in the provision for airflow shut off and filtering for fire fighting and protection of the engine from foreign object damage. This latter requirement is universally accepted and is met by various combinations of wire mesh duct screens and bellmouth covers. The designer may locate these screens as convenient but placement aft of distortion-producing acoustic treatment will provide a bonus of a reduced requirement for flow mixing length. References 42 and 50 may be used to calculate pressure loss due to screening.

Though CO_2 flooding systems are available in many present test cells, there is less than complete agreement about the necessity of their incorporation in future facilities. Increased size and the greater CO_2 capacity required to effectively flood large cells has escallated the associated installation costs. Larger cross sections also imply longer operating times for hatch shut-offs and further reduce system effectiveness. Operator experience indicates that the Cardox flood system may itself be more of a hazard than the fires it is intended to prevent due to casualties possible from accidental actuation. Many aircraft powered by turbojet engines now incorporate quick shutdown systems and local application of extinguishing agents. Similar provisions in test facilities may eliminate the requirement for a quick-acting inlet shutoff. This is worth detailed investigation since it would remove the only inlet component requiring regular maintenance and would represent a considerable savings in construction cost [Refs. 16 and 34].

The cell access doors and their actuation systems are the other inlet components with maintenance requirements in a side loaded configuration. If the front loaded layout is selected, it may be necessary to include articulated acoustic treatment and flow straighteners which will increase loading time somewhat and be sources of additional maintenance requirements. In either case, sliding or outward opening doors provide designed-in safety.

Inlet design can make a substantial contribution to overall cell performance and to reduction of operating costs by the inclusion of a mounting frame for air filtration panels. Passing the flow through a ten micron filter will increase the life of all cell components from acoustic sheet metal to temperature probes [Ref. 16]. These panels are low in cost and are reuseable; the increase in cell depression is minimal. The air quality at nearly all facility sites is now poor enough to make this a profitable addition to new designs; this quality is not likely to improve much in the future.

B. TEST SECTIONS

1. Engine Handling and Access

Efficient operation of production type test cells require that the non-running time of the engine in the cell be minimized. The engine-test bed adapter system is the best means of reducing this time and has demonstrated satisfactory performance at many modern facilities. Since the adapter is attached to the engine in the preparation area the handling system must transport the completed unit. Selection of the optimum handling method requires consideration of the following factors:

a. Tracked dollies prevent damage to concrete decking and eliminate traffic accidents that can occur with free dollies, but they are relatively inflexible in accepting widely varying engine sizes. They are also reasonably complex when used with engine-cell adapters and may require more maintenance then overhead handling systems of equal capacity.

b. Free dollies may require special high cost decking for use with large, heavy engines and, when designed to handle the engine/adapter combination, they may not be suitable for general use elsewhere in the repair facility.

c. Bridge cranes lack the ability to serve both the test cell and a large preparation area. They also require larger and more expensive cell access doors.

d. The overhead monorail, either powered or free, minimizes access door size, can be tracked to multiple prep area stations, is suitable for the engine/adapter combination, can incorporate the hoisting unit required for cell loading, is flexible in size and shape capacity, and allows required maintenance to be performed outside the cell. This system is in operation [Ref. 11], in present facilities; the only difficulty has been the effect of the rail on inlet aerodynamics. A streamlined track shroud or submersion in the overhead surface may reasonably be expected to eliminate unacceptable flow distortion.

Access to the installed engine must be convenient and safe. The access structure must not produce flow distortion or recirculation during test operation and must be adjustable in height and lateral position. Current systems utilize access structures which retract into the interior cell surfaces [Refs. 16 and 33]. Deck mounted service stands will be continually subject to corrosion damage from spilled engine fluids and cleaning solvents, and they must support transport dollies if an overhead system is not employed. A valuable addition to operational efficiency can be made by the designed inclusion of storage space for servicing and troubleshooting equipment which is convenient to the work area. Adequate lighting of the side and bottom engine surfaces is essential and at some sites the installation of radiant heating units can greatly increase efficiency and safety.

2. Acoustic

In current test cells it is the acoustic portion of the engine environment which is least similar to that of the aircraft-installed engine. Reflection from the smooth concrete surfaces surrounding the engine subjects the engine casing and external accessories to acoustic power levels several times those present in an aircraft. No reliable data on damage caused by this is available but it is certain that it is not beneficial. Some operators subjectively estimate that a 10-15% reduction in component life is attributable to this source. New cells should be designed to minimize the acoustic energy reflected onto the test engine either by absorbing it at the wall surface or directing it away from the test section. Reference 57 illustrates the substantial reduction possible with commercial absorbent materials. The effectiveness of directionally reflective surfaces is illustrated in Ref. 39; this option has the advantage of nominal cost in new construction.

3. Aerodynamics

The primary requirement for the test section is that the flow remain unidirectional and without recirculation of engine exhaust. Aft of the engine bellmouth there is no further necessity for streamlining or shrouding equipment except that even small variations of pressure along the engine casing may produce variation in the measured thrust. This will be minimized by keeping the exposed surface area between the engine and the thrust bed to a minimum and, if constant, it can be included in cell correlation factors [Refs. 8 and 37].

When the augmentation ratio is high, there is little likelihood of recirculation. When little or no augmentation air is used, the control of recirculation is more difficult and, to be flexible, new facilities must be designed for possible operation in the zero augmentation mode [Ref. 37]. Figure 9 illustrates the primary alternatives for recirculation control. The septum wall provides positive control but must be considered as a last resort due to the mechanical complexity involved in making it removable, useable with different engine inlets, and strong enough to resist the considerable pressure loading which is possible. The second alternative requires that excess air be drawn past the engine even when it is not required for exhaust cooling or

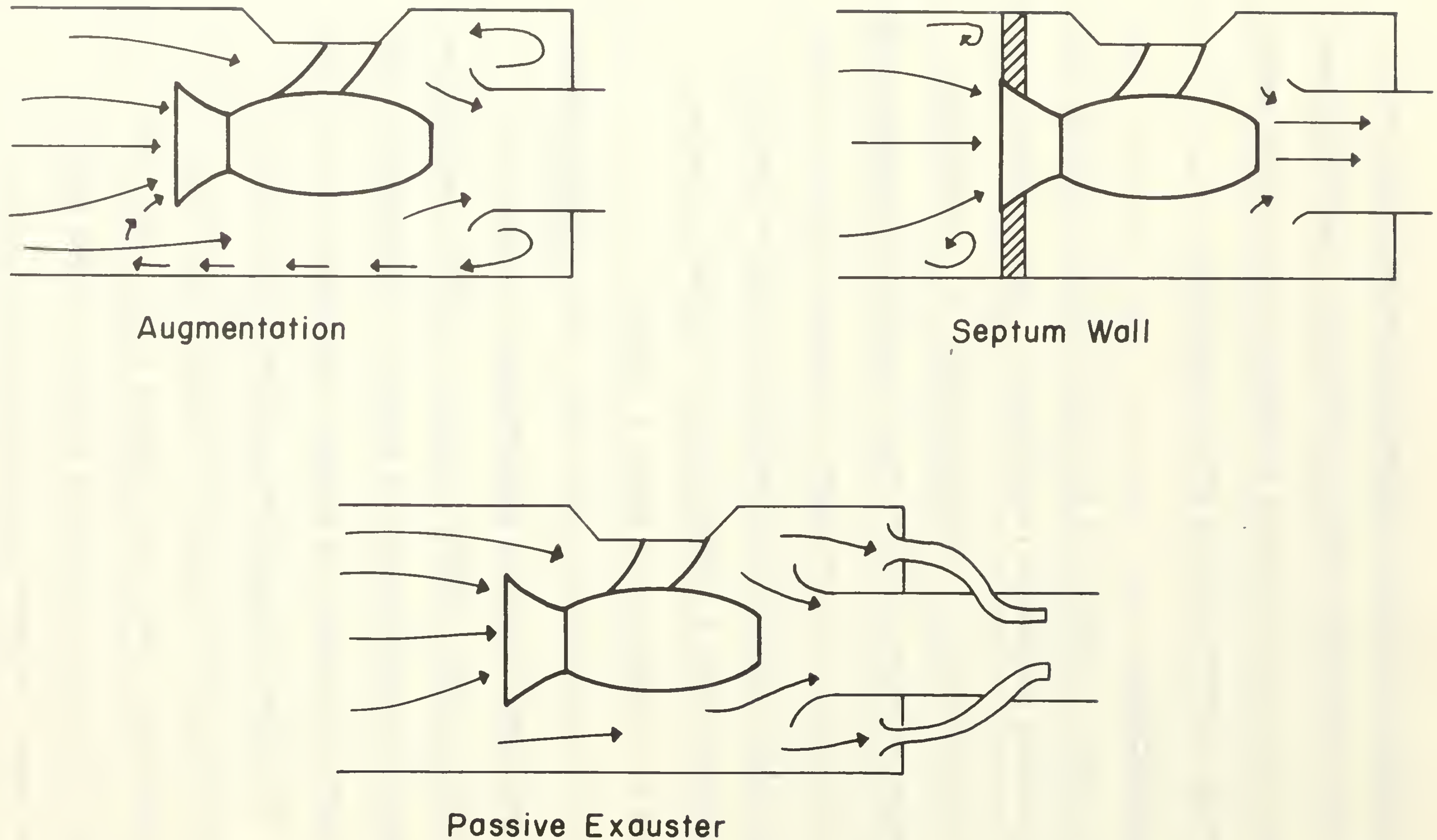


Figure 9. Recirculation Control Options.

mixing. Since this is needed only while the engine is in operation, it is logical to make the engine exhaust the power source and design the system to be entirely passive. An active exhauster powered by a separate electric motor is possible, but the flow capacity required and the additional cost and maintenance make it less than attractive. The drawback to inclusion of the passive venturi powered system is that the initial motivation for operation with a low augmentation ratio may be reduction of the flow volume to be handled by a pollution control system. If the afterburner method of pollution control is to be used the exhauster air could be added to the exhaust aft of the secondary combustion zone. In any system, if the volume flow required for control of recirculation is low enough, inclusion of the passive exhauster must be considered since it has the advantages of low initial cost and minimum maintenance requirements [Ref. 33].

Installation of cell instrumentation with the capacity to detect recirculation is a design feature which will return an excellent profit on a small initial investment by ensuring test reliability and preventing the accumulation of explosive mixtures when future engine-augmenter positions are varied.

4. Instrumentation and Mounting

A key feature of the instrumentation design is flexibility. Effective use of the engine adapter system requires that the permanent test cell portion of the equipment require little or no modification when new engines are introduced. Each adapter will be customized to a particular engine but all must appear identical to the test bed. This demands that the original design have sufficient capacity to accept the number and type of data transmission chanels required by future engines and refined test techniques. References 12, 16 and 28 illustrate current estimates of this requirement; recent experience indicates that the savings possible by limiting this capacity will almost certainly be temporary ones, since excess capacity is free of maintenance cost and can, in fact, greatly reduce cell down-time by permitting rapid shift to alternate channels when malfunctions occur. Maintenance can then be performed at scheduled times. The importance of this capability cannot be overemphasized since most operators report that the majority of cell down-time results from instrumentation malfunctions.

Though cell accessibility may be complicated by the use of the overhead thrust bed, its advantages more than compensate for this, and it is now recognized as the best design for future test cells. Among these advantages are: natural similarity to aircraft engine mounting methods, ready compatibility with monorail handling, freedom from corrosion by collected fluids, flexibility in engine positioning, and the availability of advanced design experience. It is possible to utilize a single step plug-in of the adapter to the test bed but experience indicates that separating the connection of the physical support from the plug-in of the instrumentation leads enhances system reliability [Ref. 16].

For facilities required to anticipate a wide spectrum of thrust levels, it is possible to improve thrust measurement accuracy by using a three component system: test frame, thrust bed and engine adaptor. With this arrangement the thrust bed may be changed to one having flexures with maximum sensitivity in the desired range [Ref. 16]. Investigation of the possibility of eliminating the direct thrust measurement system has shown that while it is technically feasible, the savings in engineering complexity are small and are offset by increased requirements for other types of instrumentation. In the view of most users, deletion of the direct thrust measurement system is not justified [Refs. 12, 16, and 39].

5. Auxiliary Subsystems

One of the most persistent failures in test cell design has been lack of subsystem growth potential. Rapidly increasing fuel consumption rates have made extensive rework of some facilities necessary and restricted the operation of others [Refs. 12 and 16]. At several installations the supply of starting air has proven inadequate almost before the cell was placed in operation [Ref. 12]. For facilities requiring water for exhaust gas cooling or scrubbing it is imperative that future capacities be determined since they may well be double or triple those required to test current engines. In all these subsystems, doubling the design capacity increases initial cost only about 20 per cent while a similar change in an existing system may easily double the original cost and require extended facility closures.

In addition to sufficient capacity, the fuel system should be designed to permit future expansion to at least a two fuel operation [Refs. 2, and 58]. Again, providing this flexibility during design will cost far less than adding it later. Design of all subsystem controls should include maximum utilization of advanced control and monitor technology. The number and criticality of the subsystems which must be included in a turbojet test cell demand that careful attention be given to design of interlock controls providing fail-safe operation. There is no reason for operator error or an undetected malfunction to cause major damage to the engine or test facility. The electrical power dissipation, dynamometer and fire extinguishing systems should also be routed through a master interlock control.

C. CONTROL CENTER

The choice of data acquisition method will establish the requirements for the design of this area. In a facility requiring manual data recording, 25-30 per cent of the total engine running time is occupied solely by data acquisition. Additionally, two to three minutes may elapse between the first and last data reading at each operating condition. Thus the justification for the higher cost of automatic data acquisition systems includes reduced cell time per engine (with accompanying reduction for fuel, utility and pollution abatement loads) and increased test credibility due to the simultaneity and accuracy of data.

Sufficient incentive exists for the inclusion of automatic data scanning equipment in all future production test cells. It is possible to automatically acquire data and simply supply it as a printed record. But the nature of the data processing normally required is such that its inclusion within the automatic equipment is simple and effective. It can then be presented in a written format acceptable to the user [Fig. 10], or as real-time operator assistance. Further extension of data system sophistication is possible and may be justified in the following areas:

a. Individual engine history records containing either rework/ repair testing results or expanded to include in-service information [Ref. 59].

b. Safety monitoring capability to provide warning of impending failure or to initiate shutdown or other corrective action.

c. Operator assistance in the form of step-by-step procedural instructions and malfunction analysis.

The computer centered data system can also be operated in a closed loop mode with engines tested under fully automatic control [Refs. 58 and 16]. It is unlikely that this could be economically justified in future production type facilities, however, since manpower savings would be small (installation and repair still required) and the cost of a reliable system high.

Long range economy is best served by including in the initial system design excess capacity to permit processing of additional data

```
                 ***** TFE - 731 ENGINE *****
GUARD SYSTEM DATA            SERIAL NO. 7307                DATE   2' 7/72
                                                            TIME     39-22
CYCLE      1                                                PAMB    14.76
IDLE FOR 1 MIN


** CALCULATIONS **
N1C2                 5789.0  PT2                    14.76  WFCOR            197.13
N2C2                16233.5  TT2                    140.4  TSFC             0.9065
N2/N1                 2.804  FNCOR                 202.17  PDWF             -0.574
GEN POWER             0.000  HYD PUMP NO.1 PW 397.328
TOTAL EXT POWER 513.647  HYD PUMP NO.2 PW 116.318


** MEASURED DATA **

SPEEDS-                      THRUST (LBS)          203.05  FUEL FLOW MAIN   198.00
N1 (RPM)             5789.0  POWER ANGLE            38.60  FUEL FLOW VERFY  199.13
N2 (RPM)            16233.5

PRESSURES - (PSI)
COMP DISCH            27.76  OIL TANK VENT           0.00  PT7 LPT DISCH     15.04
FUEL PUMP INLET       67.51  NO.6 BRG SCAV           0.00
F/O (OIL IN)           0.00  TOT ENG SCAV            0.00
FAN G/B(OIL IN)       47.07  OIL PUMP DISCH          0.00

TEMPERATURES - (DEG F)
FUEL                   55.2  TT7 LPT DISCH 180        0.0  TT5 HPI DISCH     838.2
F/O (OIL IN)            0.0  TT7 LPT DISCH 181        0.0  HPC DISCH           0.0
FAN G/B(OIL IN)       135.4  TT7 LPT DISCH 184        0.0  SURGE VAL D 805    84.3
HYD PUMP IN           130.4  TT7 LPT D+SCH 185        0.0  SURGE VAL D 806     0.0

FAN G/B SCAV          124.1  NO 4 BEARING             0.0
NO 4-5 BRG SCAV       151.0  NO 5 BEARING           168.7

VIBRATION - (MILS)
TURB VERT             0.680  COMP VERT              0.590  B-FAN ORB VERT    0.000
TURB HORIZ            0.070  COMP HORIZ             0.770  B-FAN ORB VERT    0.000
```

Figure 10. Typical Data System Output.

without major remodeling. Removeable flooring in the control area is an excellent means of providing both maintenance access and ease of modification. The sensitivity of electronic data systems to interference and damage from acoustic, vibrational, and electromagnetic energy exceeds that of the human operators and reinforces the necessity for the inclusion of appropriate types of shielding in the design of the control area [Refs. 12, 14, and 28].

Replacement of the viewing window by a closed circuit TV monitor simplifies the insulation problem and increases safety. To justify its cost, the video monitoring system must be capable of providing resolution and discrimination comparable to that of an operator present in the cell. With carefully considered lighting and placement, accurate color reproduction, magnification to a one foot focal distance, and full articulation it will be possible to eliminate the necessity for in-cell operator inspection. This could reduce run times and allow leakage checks at other than idle power settings. For some facilities the addition of a video recording capability to the monitor system may be advisable. Having low initial cost, adaptable to fully automatic control, and requiring little maintenance, a video tape recorder could provide accurate records of malfunctions and permit continuing studies of cell efficiency. A recorder could also supply effective training material for operators when new engine models are introduced or new test procedures are initiated.

Modular design of the control station and provision of ready access to the installed equipment should be of prime concern to the designer [Refs. 16 and 28]. Some operators presently feel that audio monitor capability should be provided, and an earpiece adaptation of the required intercom system could be employed for this purpose.

D. AUGMENTER AND EXHAUST TREATMENT

1. General

An efficient, flexible and reliable exhaust system is perhaps the most critical segment in test cell design, yet the present level of engineering sophistication in this area is still elementary. Justification for the above statement is the recent change in the design criteria of cell exhaust treatments. Early designs were primarily built to lower exhaust temperatures to levels that would not unacceptably shorten the life of installed noise abatement systems. This was accomplished by mixing the jet exhaust with secondary air. Past acoustic practices have been re-examined [Refs. 60, and 61], and in many cases stricter requirements have been formulated [Refs. 15, 12, 25, and 58].

Additionally, attention is now being focused on reducing the air pollution levels of jet engine test cells. Generally, test cells are placed in a different regulatory category than are jet aircraft themselves. They are classed with other stationary sources [Refs. 62, and 63].

2. Aerodynamics and Thermodynamics

A poorly designed augmenter system may be one that acts, as an unnecessarily powerful jet pump. In this situation too much secondary or cooling air is entrained with the engine exhaust, causing higher than designed cell airflows and cell depressions. Also, larger than design airflows will increase distortion levels and possibly disrupt smooth engine operation [Refs. 37, 15, and 6]. Large air flow can also cause errors in thrust measurement.

At the other end of the design spectrum is the system that fails to induce enough secondary airflow, and thereby fails to prevent the problem of recirculation of exhaust gases. Excessive exhaust temperature may also result.

The problem of excess secondary airflow has been encountered at several facilities. At North Island a flange has been added to the augmenter bellmouth, restricting the flow of secondary air. This is not a smooth design aerodynamically, and the capability of this facility to handle large bypass fan engines or other high flow rate engine types is severely limited with the present flow restriction. A second solution is to install orifice plates within the augmenter itself to reduce the available flow area [Ref. 20]. This type addition is slightly more flexible than the former since various size plates may be installed depending on the flow characteristics of the particular engine under test. These fixes are shown in Figure 11, a and b.

At the United Air Lines facility in San Francisco, secondary airflow in their new large jet engine test facility has been estimated as being almost twice as high as was originally anticipated [Ref. 17]. This condition has not exceeded cell structural limits with the present engines being tested, (JT9D, CF6), but the cell performance with advanced technology engines which may reach the 100,000 pound thrust category will be marginal. This situation indicates the need for close attention to augmenter design and more thorough analysis of the ejector process.

Secondary air provides the necessary cooling of the engine exhaust and prevents recirculation. For a turbojet engine operating out of afterburner mode an augmentation ratio of 2:1 has been set as a reasonable design goal [Refs. 12 and 15]. Augmenter performance is a function of the area ratio of the augmenter and exhaust nozzle, the length of the augmenter, the position of the exhaust nozzle relative to the entrance of the ejector tube, and velocity ratio. Most recommended test cell augmentation ratios for fan engines vary from 0.25:1 to 0.5:1 for high bypass engines and up to 1:1 for low bypass types [Refs. 12, 15, 5, and 64]. Appendix A contains the standard definitions of augmentation ratio for turbojets and turbofan jets.

Besides its function of providing the means of mixing and cooling the engine exhaust, the ejector system must overcome the various pressure drops in the inlet and the exhaust systems. Figure 13 shows the general pressure pattern within the test cell. Basicly, momentum is transferred to the secondary air, thereby increasing its pressure.

Studies have been made to determine the mixing characteristics of jet pumps [Refs. 65 thru 74]. These indicate that for each characteristic exhaust and secondary airflow combination there is an optimum length and diameter mixing tube. However, because of the cost of construction of the exhaust facilities many trade-offs must be made, and a flexible design must be selected that will work reasonably well over the range of engines to be tested.

A second method of cooling the exhaust is to use water spray cooling. This method is mandatory for engines operating in the afterburner mode, but may be used in other modes as well. Studies have been carried out [Refs. 15 and 27], which indicate the amounts of air, water or both which are required to cool exhaust gas temperatures to acceptable levels. When suitable amounts of water cooling are used, secondary airflow can become negligible. However, compromises must be made to determine the amount of water used. At the present time most of the water used in spray cooling is lost through the stack. At several locations, including NARF North Island, fresh water supplies are at a premium; availability may dictate the design option chosen.

Where water cooling is necessary and available, difficulties remain in devising means whereby the high temperature jet core may be thoroughly penetrated by water streams. It is known [Ref. 18], that even high pressure water jets have little success penetrating into the core of a high speed flow. Various designs have been developed, including concentric rings, water spargers and bounce sprays [Refs.

20, 19, and 75]. These designs, however, have not been optimized for facilities required to test widely varying engine types.

Matching augmenter characteristics to individual engines will be difficult, particularly where low augmentation ratios are desired.

Variable area nozzles are common for afterburning engines. The exhaust from the fans of high bypass engines is at a relatively low energy level, and since it contains no products of combustion, separate ducting may be desirable. The Pegasus engine used in the Harrier aircraft requires complex ducting during test cell operation [Ref. 5].

Prevention of thermal damage to the augmenter must be considered. In the entrainment zone [Fig. 12], the walls are subject to radiant heating, while in the fully developed mixing zone they are heated by convection. Water jackets may be necessary during testing of afterburning or high turbine inlet temperature engines, particularly if the selected exhaust treatment system requires a low augmentation ratio.

3. Acoustic Treatment

Noise sources that must be treated by exhaust systems are: turbomachinery generated noise, combustion noise, turbulent noise generated by the interaction of the jet exhaust and the secondary air and the turbulence in the exhaust itself [Refs. 76-81]. In the entrainment zone the shear stresses are high and the turbulence level is relatively low, creating most of the high frequency noise emanating

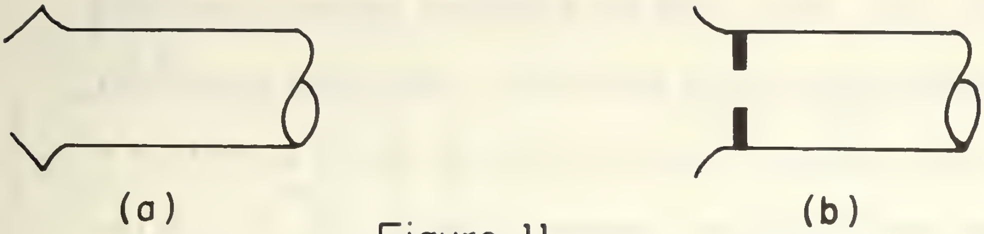


Figure 11.

Augmenter Flow Restrictions at Two Navy NARFs.

(a) Flange installation at NARF North Island

(b) Orifice installation at NARF Alameda

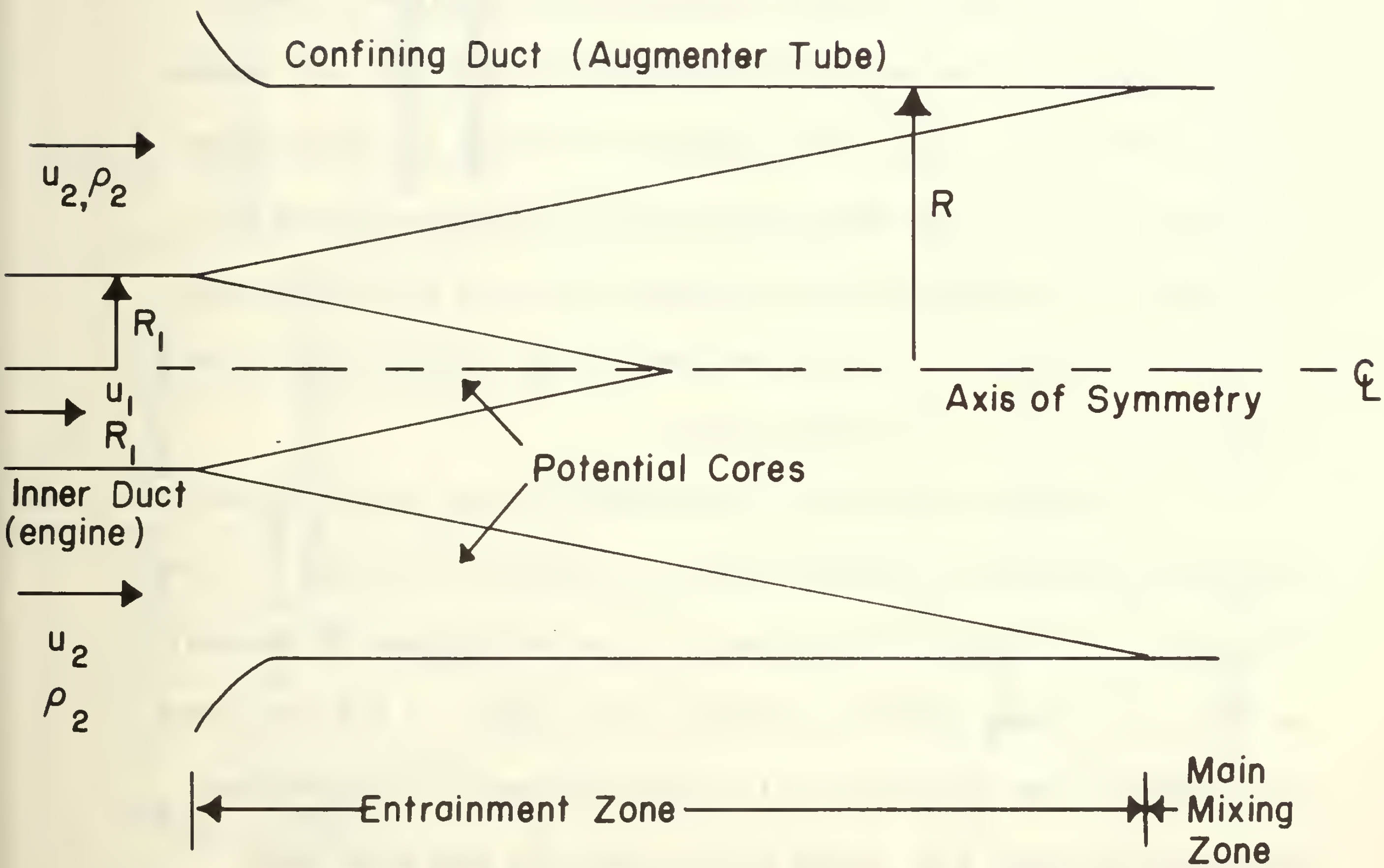


Figure 12. Jet Mixing Zones.

from the jet [Ref. 82]. Most of the low frequency sounds, those which contribute the most to the overall sound level, come from the portion of the exhaust beyond the potential core; the peak of this sound is at a wavelength about three times the diameter of the jet [Ref. 82]. It is this low frequency sound that is most difficult to attenuate. The higher frequency noise of machinery is easily abated with standard techniques which include baffles of all types, lined passages and bends, and tubular exhaust passages [Refs. 15, 33, and 37].

The properly designed augmenter can contribute to the overall reduction of noise; experimental results [Ref. 83], have shown that jet noise can be reduced by a factor of 5 (7db) in an ejector noise suppressor. It was also shown that the initial mixing conditions and the length of the injector are more important factors in obtaining this attenuation than the area ratio of the tube and jet or the position of the primary jet relative to the ejector inlet.

Methods of breaking up the continuity of the jet and increasing the frequency of the exhaust noise are discussed in Section IV. The utilization of a colander in the form of a cone or a cylinder is presently preferred over other options in modern cell designs. It has been found by experience that a hole size 1-1/4 inch in diameter is the smallest practical size [Ref. 15]. Holes smaller than this tend to be easily blocked due to impurities in cooling water as well as particulate matter present in the engine exhaust. Standard practice has been to uniformly space the holes over the surface of the colander, with total hole area

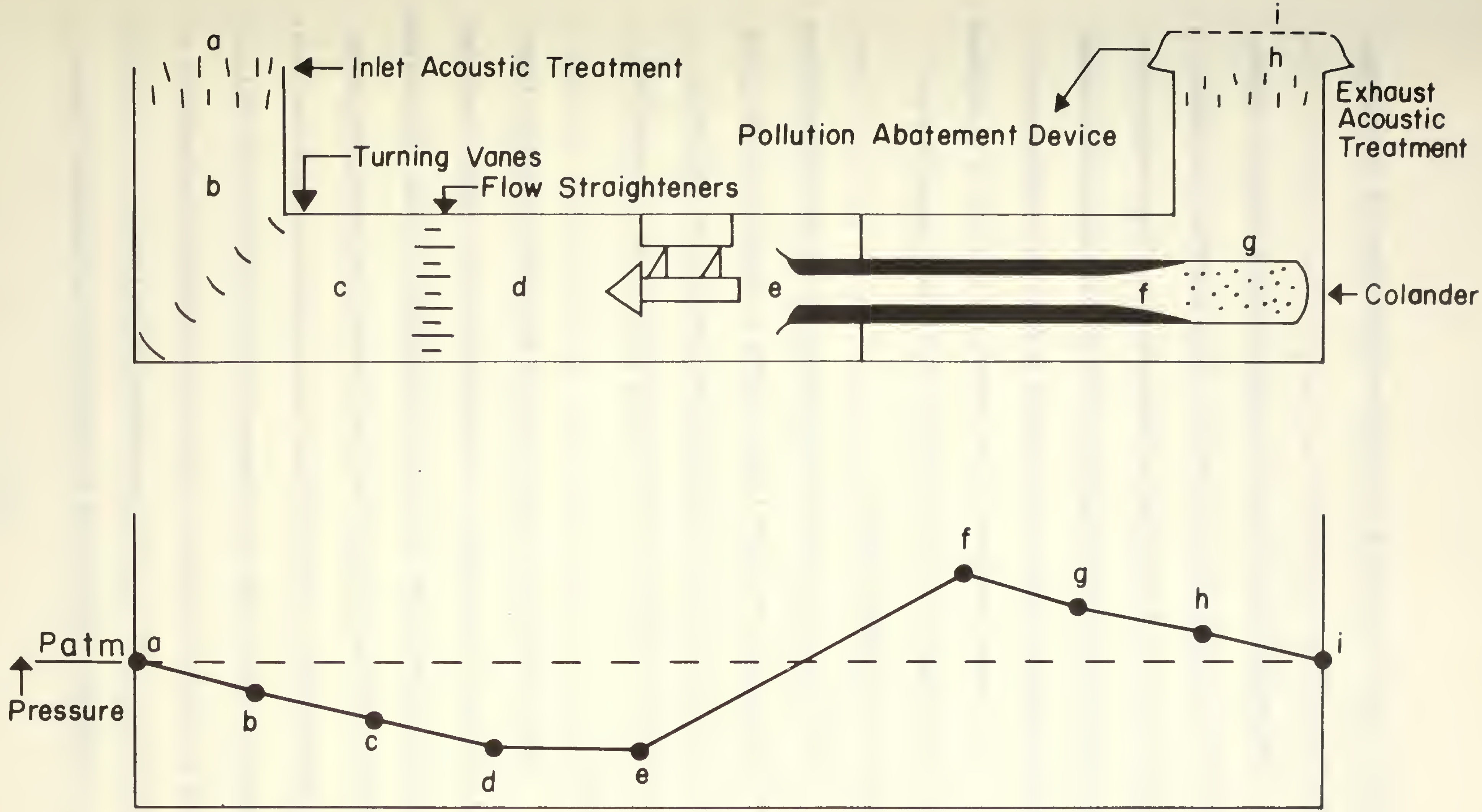


Figure 13. Test Cell Pressure Profile.

40 to 60 per cent in excess of the cross sectional area of the augmenter tube itself [Refs. 21 and 15].

An exception to this practice has been introduced in some smaller Navy "C" cells [Ref. 21 and Fig. 5]. In these cells holes were placed only in the lower half of the colander. This design has exhibited a serious shortcoming in that flow through the exhaust stack is very non-uniform; in fact, some points in the stack exhibit zero velocity. This causes portions of the acoustic treatment to be exposed to higher than design flow rates, thereby shortening useful life and decreasing overall performance.

Analysis must be done during design to ensure adequate flow conditioning over the operational range of the proposed test cell. The designer must ensure that enough pressure rise will be obtained to overcome any flow blockage that may be present under all operating conditions.

Unwanted acoustic energy may be generated by obstructions present in the ejector assembly. These include spray rings or nozzles, diffuser rings and any other hardware installations. These obstructions increase the turbulence level of the flow, thereby increasing the noise sources within the flow. The merits of each proposed installation must be weighed according to the use intended for the individual test cell. Care must be taken that natural frequencies of installed components are not activated by the driving frequencies of the flow.

Possible exhaust stack treatments are as varied as those intended for use in the inlet. Options include lined bends and passages, tubular mufflers, sinuous passages or straight passages [Refs. 28, 29, and 15]. Steel Helmholtz resonators have been investigated by General Electric [Ref. 15], and have been found to be unsatisfactory for their own use; this approach has been successfully taken by Aero Systems Engineering, however [Ref. 39]. Differences are in the cell utilization of the two operators, and in the acoustic characteristics of the engines tested.

A primary concern is to develop a system which will withstand a moderate range of temperatures and wide range of velocities. Most installations have been designed to withstand exhaust stack temperatures in the 450-550^{o} F range, with a maximum of 600^{o} [Ref. 15]. At one time NARF North Island attempted to maintain temperatures below 200^{o} in the non-afterburning mode by water cooling. However, it was impossible, with the existing water spray design, to operate the afterburner and maintain stack temperatures below 450^{o}, and the installed acoustic treatments were subjected to such severe thermal shock that their useful life was drastically shortened. Within practical limits a constant stack temperature should be maintained in all test modes.

Because of the varied sizes and characteristics of engines that will be tested in new construction test cells, consideration should be given to the possibility of providing variable area exhaust stacks. Methods of accomplishing this vary from simply blanking unnecessary portions of the stack with pre-fitted metal shutters according to the flow requirements of the engine under test to a movable cover over the stack opening which is programmed to provide optimum flow area (and available acoustic treatment) for a given engine power level. By designing the basic exhaust system to handle the largest forecast air-flow with the additional capability of efficiently handling much lower flows the problem of test cell obsolescence caused by advances in engine technology can be avoided.

4. Emission Control Devices

In the future, major design effort must be devoted to pollution abatement systems. It has been established by Executive Order 11282, May 26, 1966, that Federal installations comply with local environmental protection requirements. At the present time most emission requirements which are applicable to test facilities deal with the particulate emissions which cause visible pollution. Future legislation will limit emission levels of invisible noxious gases, carbon monoxide, oxides of nitrogen and sulfur dioxide. Studies have been conducted to determine exhaust emissions of gas turbine engines [Refs. 63, and 84-89], and although the exact emission levels are not agreed upon, most figures mutually agree on an order of magnitude basis.

The abatement system chosen for test cell operation must first remove visible particulate emissions. California legislation limits the deviation from a maximum of 20 per cent obscuration (#1 on the Ringleman scale) to three minutes out of every hour.

Except at idle, gas turbine engines emit very low levels of unburned hydrocarbons and CO, so that attempts to reduce these should concentrate on low flow rate conditions [Ref. 84].

By 1975 Los Angeles County will limit emission of oxides of nitrogen to 225 ppm [Ref. 62]. New developments in engine technology resulting in high pressure ratios and high combustion temperatures have raised the levels of these oxides in engine exhausts [Ref. 84]. The chosen abatement system must at the very least not add to these levels and ideally should reduce them.

The installed system must be able to remove unburned fuel from the exhaust flow. Estimates are that in the afterburner mode turbojets exhaust about 10 per cent unburned fuel. Also, the ability must be retained to purge unwanted fuel from the exhaust drainage system. Prior to light-off it is Navy practice to "dry run" the engine; that is, the engine is windmilled and the throttle fully opened to check for leaks. This results in relatively large amounts of fuel being dumped directly into the exhaust system.

Emissions of sulfur dioxide will not be a problem as long as the current restrictions on sulfur content of fuel are maintained. Present restrictions limit the sulfur content to .3 per cent, and most fuels contain even less.

Although advances have been made in combustor technology, completely clean jet engines are not yet a reality. NARF Alameda was recently cited in violation of local standards while testing a high time engine configured with "clean" combustor cans. One source [Ref. 63], theorizes that reactions within the cell exhaust system change the character of particulate emissions, either in size or number, so that visibility obscuration is greater at the test cell exhaust stack than at the engine tailpipe.

Interim solutions for reducing smoke involve the use of fuel additives. United Air Lines in San Francisco utilizes CI-2 in their testing. Additives coat engine hot section parts, and the effect of adding heavy metallic vapors to the exhaust is under continuing investigation by the EPA.

Early studies of pollution abatement systems have resulted in the selection and development of a nucleation scrubber [Ref. 75]. Other devices analyzed include filtering devices, venturi scrubbers and electrostatic precipitators. These have been evaluated as unsatisfactory from considerations of safety, flexibility and economy in Ref. 75.

Filtering devices alone present problems because of their tendency to become clogged by particles entrained in the exhaust. Additionally, they require extremely low flow velocities, and are not effective in removing noxious gases.

The primary drawback to the venturi system is its inability to operate efficiently over greater than a 10 per cent interval away from its design point, which is an unacceptable restriction in light of the fact that air flows vary as much as sixty to seventy per cent from idle to full power setting. A possible solution to this would be the installation of a bank of venturis, entailing high initial costs and complicated flow controls.

The present shortcoming of electrostatic precipitators is the inability to completely prevent fuel buildup on and around the electrodes; this condition creates the danger of an explosive discharge. Also, these systems cannot remove noxious gases or oxides of nitrogen.

Nucleation scrubbers work by process of creating large particles by condensation of vapor from a saturated vapor. The nucleates are the particulate matter already present in the exhaust. The enlarged particles are then removed by impaction in the scrubbing system. A prototype scrubber system developed by Dr. A. Teller (Pat. #3,324,630) has been installed by the Navy at NARF Jacksonville. This particular scrubber has the capacity to handle large changes in flow volume, can reduce noxious gases and unburned fuel and with modification can remove much of the oxides of nitrogen and sulfur if such action is required. Installation of this scrubber is also anticipated at NARF Norfolk. The primary drawback at present with the scrubber system is its high initial costs. At its present level of development this system is not considered the ideal solution, and investigation is being carried out in other areas as well.

The nucleation scrubber as well as the other alternatives discussed are all similar in that they function by physically removing particulates and unwanted gases; a second class of installations acts by converting unwanted pollutants to harmless chemical species. These include afterburners and catalytic converters.

Northern Research and Engineering Corporation has proposed a thermal converter installation for test cells [Ref. 62]. This reference is a comprehensive discussion of the feasibility of such an installation and the justification for Navy procurement in light of future requirements for pollution control. At the present time much work remains to be done in conducting recommended studies and testing.

The installation of a converter system will require close matching of the test section, engine and exhauster itself since the proposed system requires a low augmentation ratio.

The final selection of an abatement system will be based on its flexibility and economy. It must be able to operate over a wide range of exhaust velocities and temperatures. The initial cost of procurement and installation must be low, as must the cost of operation and upkeep. The system must be reliable enough to allow firm scheduling of cell down time with the minimum amount of unscheduled maintenance. An additional factor will be the ease with which the abatement system may be retrofitted to existing test cell structures.

The creation of secondary pollution must be avoided. Thermal pollution of natural water supplies is a real possibility in systems requiring heavy cooling. Also to be avoided is the creation of additional, unwanted noxious gases or other undesirable products of combustion if an additional combustion process is used.

Maximum allowable temperatures, pressures and velocities will dictate the level of required protection of hardware exposed to the jet exhaust. Because of the temperatures encountered during after-burner runs it may become necessary to water cool certain exposed parts. Refractory linings have been considered, but were rejected for economic reasons [Ref. 62].

Complete acoustic analysis must be completed to ensure that the natural frequencies of equipment exposed to the flow not be excited by the frequencies of turbulence generated noise.

Finally, the design of adjustable components should be kept as simple as possible. Operators are wary of too much gadgetry in test cell design [Refs. 17 and 20], and cell down time increases with the addition of mechanical sophistication. All facilities must be designed to operate with the minimum amount of required upkeep.

APPENDIX A

Equivalent Augmentation Ratio for Turbofans

Test Cell Augmentation ratio is defined as

$$A = \text{Augmentation ratio} = \frac{m_i - m_e}{m_e}$$

where m_i = total mass flow in the inlet stack

m_e = mass flow passing through engine

Bypass ratio for a turbofan is defined as

$$B = \frac{m_e - m_c}{m_c}$$

where m_c = mass flow through engine core

Cooling air for a turbojet is $m_i - m_e$. For a turbofan cooling air is $(m_i - m_e) + (m_e - m_c)$, if energy added by fan is neglected. Manipulation leads to

$$A_{eff} = A + B + AB = \frac{m_i - m_c}{m_c}$$

Appendix B

Firms with Experience in Test Cell Design

The following firms are known to have valuable expertise in areas pertinent to test cell design. The list is by no means complete, but it will give the potential operator an excellent starting point for contacts regarding facility design. Additionally, the customer should contact the large number of test cell operators to ascertain any problems which inevitably arise. These operators include airline overhaul facilities, engine manufacturers and military rework facilities.

1. <u>Aerodynamics and Engineering</u>

Aero Systems Engineering Inc.
358 E. Fillmore Avenue
St. Paul, Minn. 55107

Burns and Roe Inc.
9800 South Sepulveda Blvd.
Los Angeles, California 90045

FluiDyne Engineering Corp.
5900 Olsen Memorial Highway
Minneapolis, Minn. 55422

Gustav Getter Associates
524 North Avenue
New Rochelle, New York 10801

Northern Research and Engineering
200 Vassar Street
Cambridge, Mass.

Price-Clark Industries
420 South Pine Street
San Gabriel, California 91776

Sverdrup and Parcel and Associates
800 North 12th Blvd.
St. Louis, Missouri 63101

2. Acoustic Controls

Aeroacoustics Corp.
P. O. Box 65
Amityville, New York 11701

Bolt, Beranek and Newman Inc.
50 Molton Street
Cambridge, Mass.

Industrial Acoustics Company
380 Southern Blvd.
Bronx, New York 10454

Koppers Company Inc.
400 Commonwealth Avenue
Bristol, Va. 15219

R.I. Corporation
499 West 2nd Street
Ogden, Utah 84402

The Soundcoat Company, Inc.
175 Pearl Street
Brooklyn, New York 11201

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13. ABSTRACT

A review is made of test cell design options in order to identify characteristics of jet engine facilities to be constructed in the 1970's and designed to be operable for a minimum of twenty years. The necessity of providing replacements for many current facilities is documented, and the factors which will ensure future production capability and economic feasibility are detailed. Present turbine engines are reviewed and projections of future engines and aircraft are made. A confidential supplement is available for qualified recipiants.

Experimental investigations of inlet flow patterns and engine exhaust augmenter relationships are being carried out. Results will be published in thesis form in October, 1972, by the Naval Postgraduate School, Monterey, California.

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	ROLE	WT	ROLE	WT	ROLE	WT
Future jet engine developement						
Jet engine test facilities						
Test cell design						
Environmental protection						
Duct flow						
Acoustic control techniques						
Jet mixing						
Industrial safety						
Automatic data acquisition						